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### General Theory of Multicriteria Analysis and Life Cycle Assessment

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## Chapter 2

# General Theory of Multicriteria Analysis and Life Cycle Assessment

### 2.1 Objectives of the Proposed Methodology and Its Application

As reported in the Chap. 1, one of the most critical problems to be considered in all production processes of the agro-industrial sector is represented by the environmental impact of each phase of the working chain, in terms of both consumption of non-renewable resources, emissions of greenhouse gases, by-product reuse and waste disposal. Moreover, these environmental aspects must be evaluated assuring the technical feasibility and the economical sustainability of the proposed solutions.

This is not an easy task to accomplish, since such processes are extremely heterogeneous, due to the variety of environments in which crops grow, to the different typologies of cultivars of each crop, to the various levels of mechanisations in fields, and so on. The life cycle assessment (LCA) methodology has proven to be one of the most effective tools for carrying out the environmental analysis, even if the large variability and complexity of possible scenarios often determine a huge amount of configurations to be investigated, which require considerable computational time and resources. Therefore, some sort of pre-filtering is required which should be capable of selecting the most relevant cases to be investigated by means of LCA.

As a consequence of the previous considerations, the innovative approach proposed in this book is based on the implementation of the multicriteria analysis (MCA) and the LCA: particularly, the application of the MCA to the alternative solutions allowed to select the most suitable ones in terms of economical and environmental sustainability, dramatically reducing the global number of chain configurations to be investigated by means of LCA.

In the following paragraphs the fundamentals of the two methodologies are briefly illustrated, reporting also some indication about the main common choices adopted in the development of the proposed applications.

## 2.2 Generals About the MCA

The development of the MCA is very recent and has been carried out during the last three decades with the aim to consider several consequences of proposed solutions of various typologies of problems. Particularly, the MCA has been introduced after having realised that intuitive solutions are often not the most suitable and even if they are profitable for a specific aspect they could not be for another one. In fact, the MCA has been introduced because of the necessity to develop multiple evaluations at the same time, taking into account different points of view highlighted by different typologies of stakeholders. Therefore, this methodology can be classified as a supporting tool for decision makers because it is not able to identify the right solution whilst it is useful to organise all the available information, to supply a possible interpretation and to check the pros and cons associated with all the alternatives.

The decision process constitutes several steps: at first the different options must be identified; then a group of parameters to be used to compare the alternatives must be set; finally, all the scenarios must be judged regarding the fixed criteria with the aim to identify the most suitable options.

It is obvious that this approach may be applied in several sectors and whenever it is necessary to carry out a choice in a decision process. However, the methodology can be developed with a different type of detail according to the stage and complexity of the decision process. In fact, if the decision process is carried out at a planning stage, data available for each hypothesised scenario present lower quality and quantity than those which can be collected at successive design stages (i.e. feasibility study). Moreover, the specific sector where the decision process is developed implies a different level of complexity and a different set of criteria which can be applied more or less easily.

The MCA is not uniquely defined and a lot of techniques have been developed with the aim to better adapt the methodology to the specific problem to be solved, including all the preferences promoted by different stakeholders.

Anyway, the main structure of the MCA provides to set all the possible alternatives and to define the criteria to be used for the evaluation.

Particularly, the MCA has a precise structure that includes several steps (see Fig. 2.1):

1. Problem identification and objectives definition;
2. Problem structuring, defining both the options and the criteria to be used;
3. Preference modelling, where scoring and weighting are carried out;
4. Aggregation and analysis of the results;
5. Discussion and negotiation about the obtained results.

The first step is the identification of the problem under discussion, defining also the goals and scopes of the analysis. In this phase it is important to consider all the laws, local constraints and policies that usually highlight the most critical aspects and cause the most important differences between the hypothesised alternatives.

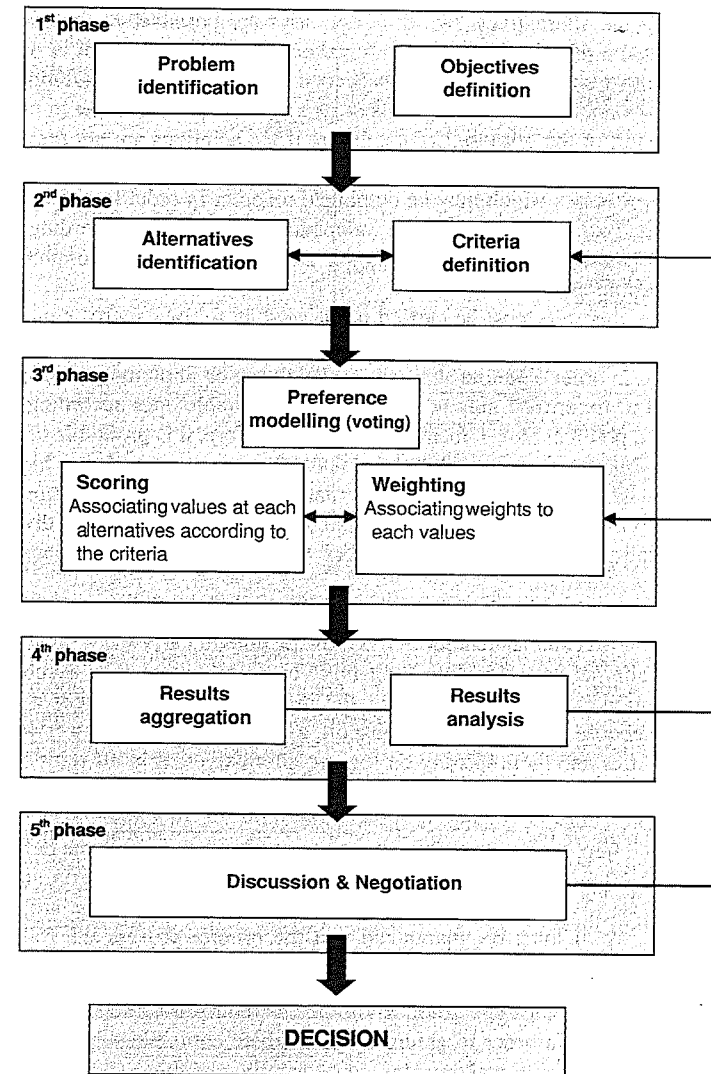


Fig. 2.1 Typical structure of the MCA

In fact, right decisions can be made only if the objectives to be achieved are clearly defined. Therefore, the goals must be specific and measurable, although they could be time-dependent, i.e. reachable in the brief, medium or long period.

Afterwards, the problem is structured fixing both the possible alternatives and the criteria to be used to evaluate and compare them.

Concerning the alternatives, two different cases are possible: in the first case they are decided a priori and the decision makers must compare them in order to indicate the most suitable ones; in the second case the possible solutions are identified by the decision makers as a result of a systematic discussion in order to assure the pursuit of the proposed goals. Often, if the solutions are not previously defined, a rational methodology may be implemented dividing the analysed process into sub-processes which may be combined together in order to obtain all the possible alternatives and which may be independently evaluated according to the fixed criteria. This approach assures to cover and to assess all the possible solutions for a specific chain.

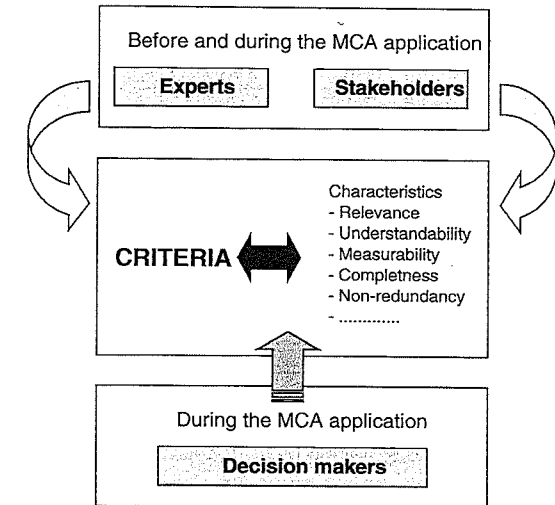
In any case, this step must be carried out according to the experts team which must have sufficient knowledge of the problem to be solved and of the site characteristics, in order to define alternatives which can be implemented in specific situations and to fix criteria able to select the most suitable ones according to the technical level, political issues, local needs, etc. Therefore, it is profitable to assure a working group where are present both local and foreign experts, able to highlight the site peculiarities and to supply an external perspective of the situation. Reference [2] also indicates the benefits originated by teams where gender diversity, mixed nationality and different perspectives (e.g. politicians, technicians, academics, etc.) are assured.

Concerning the criteria, it must be considered that they explain the point of view of both experts and stakeholders and must be able to carry out a comparison between the alternatives, therefore they must be fixed taking into account the proposed solutions in order to highlight the differences. For instance, it is not profitable to choose the means of transport as an indicator for assessing the transport facilities and their efficacy on logistic alternatives, if in all solutions the same mean or very similar typologies are adopted.

Usually, criteria can be organised in two different ways. In a hieratical structure known as value tree, the fundamental objectives are fixed and cause the definition of the specific criteria. Alternatively, it is possible to list all the criteria and in a successive phase divide them into groups characterised by the same aim to be pursued. Anyway, it must be guaranteed that the criteria possess the following properties:

- Certain value relevance according to the objectives fixed by stakeholders;
- Understandability in order to assure the immediate comprehension of the criteria by all the decision makers who, consequently, are able to use them in the evaluation and comparison of processes regarding each proposed solution;
- Measurability, meaning that at least one indicator measurable in a qualitative or quantitative way corresponds to each criterion, otherwise the criterion must be considered non usable;
- Completeness because the criteria all together must be able to cover all the proposed aims and must be able to evidence all the possible differences. This scope could not be reached at the first stage and some lack was evident in the indicators' definition only at the final stage when the different solutions are confronted.

Fig. 2.2 List of criteria characteristics and indication of subjects involved in their definition



Particularly, the comparison allows verifying if the results agree with the expected outputs; if some incoherent result occurs a specific analysis must be done and eventually it may be interesting to introduce other indicators, which may better respond to the objectives. For this reason also the decision makers may contribute to modify or integrate the criteria, but only in a second phase basing on the assumptions of experts and stakeholders (see Fig. 2.2);

- Non-redundancy avoiding that two different criteria using indirectly the same indicator overestimating a specific aspect. Moreover, it is also important to check if there are some unnecessary criteria, in order to improve the economical sustainability and to reduce the time needed to develop the MCA. However, it is possible that the double counting is done because the same indicator implies several effects from different points of view: for instance, the transport distance expressed in kilometres may be a useful indicator both for environmental and economical aspects; therefore, in this case considering twice the benefits due by reduced transport distance could be considered correct and may clearly highlight the profitability associated with solutions that adopt this logistic approach.

In addition, it must be suggested to use a limited number of criteria. Firstly, problems associated with the correct understandability of certain criteria may be avoided by the stakeholders excluding those criteria, that may result as too much technical and may require a very high level of knowledge of the environmental and/or economical issues. On the other hand, a reduced size of criteria may help to limit the risks of redundancy and double counting, contributing to permit a more easy comprehension of the expected effects of certain decisions. Finally, in this way it is possible to guarantee a better communication of the obtained outputs of the MCA.

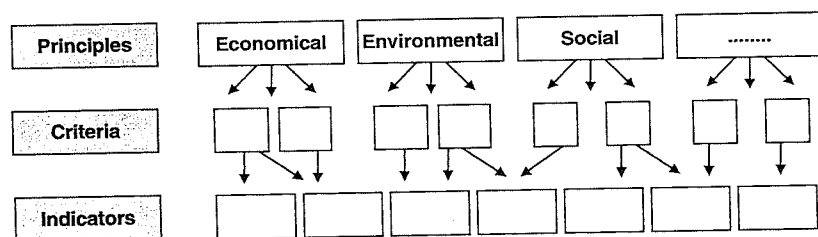


Fig. 2.3 Description of the phase of the criteria identification in the MCA

In general, the choice of the criteria and the relative indicators must be carried out considering that firstly the principles or objectives must be fixed, then the typology of the criteria must be set and finally the quantitative or qualitative indicators must be identified. This process is summarised in Fig. 2.3; moreover, some parameters may be identified in order to validate the values of the indicators defined for the evaluation of the alternatives. For instance if the environmental sustainability must be evaluated for a specific process, an adopted criterion can be the minimisation of the GHG emissions and the associated indicator can be the amount of fossil energy required: on the basis of a literature review a range of variation of this indicator must be fixed in order to facilitate the validation of the values obtained for all the alternatives and to set the suitability classes for the judgement phase.

Particularly, the principles are determined by the needs of the specific sector where the options are developed: for example, if the problem is to compare different techniques of olive oil milling, it is important both to evaluate the sustainability of the production and to assure adequate product performances according to the laws and market requirements. The subsequent step requires the definition of the criteria used to verify the sustainability of the olive oil chain: considering the most critical aspects of the agro-industrial sector, it is possible to focus the analysis on economical and environmental issues: the first ones must guarantee the convenience of the product in comparison with other products referred to in the same trade segment; whilst the second ones must highlight some benefits of the product in order to preserve the environment, making the oil more appreciable to the customers and allowing emissions within the legal thresholds. In fact, the principles become operative through the criteria, even if the criteria are not able to produce a direct measurement of the suitability of a solution as the indicators can do: the indicators are variables or parameters associated with each criteria, which allow evaluating easily the alternatives in a qualitative or quantitative way. For instance, for the olive oil production an environmental criteria could be the pressures on the global warming phenomenon and a quantitative indicator is obviously the CO<sub>2</sub> equivalent emissions. However, taking into account the complexity of the calculation of this indicator, it is possible to promote the use of other indicators, that may also be considered reliable on the basis of literature and experimental tests: for example, it is possible to choose as alternative

indicators the fertilisers requirement in the olive-grove and the electricity consumption in the milling.

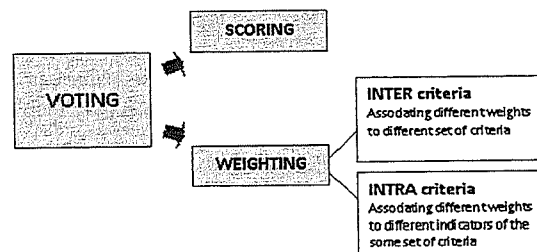
Finally, it is important to verify the values of the indicators identifying the range where they can vary. This approach may help to improve the comprehension of the indicators themselves. Moreover, a specific identification of certain monitoring procedures on the indicators may also be introduced: if the water abstraction is an indicator used in order to evaluate the environmental sustainability, it may be interesting to provide an analysis of the periodic variation of the local water availability.

Particularly, the set of criteria must be done by experts according to the decision makers: the criteria must be chosen considering the most significant aspects in relation with the priorities for optimising the choice. For instance, if design alternatives are compared, aspects concerning economics, efficiency, reliability, environment or other aspects could be analysed, but a context analysis occurs to select the most important ones. This analysis must be developed taking into account the expected benefits and the barriers, that may contrast the realisation of the proposed options.

In addition, it must be highlighted that the nature of the criteria is heterogeneous: for example, it is possible that a specific set of criteria concerns environmental impacts, another economical aspects and another health risk. When for each criterion a relative set of indicators has been fixed, it is possible to obtain a judgement of each option for each precise aspect investigated. However, the objective of the methodology is to summarise in a global judgement the evaluation of each alternative, in other words it is necessary to define relative weights able to consider the relative importance of the various aspects. This is a very difficult phase where the decision makers must justify why a specific set of criteria must be considered more important than the others. Usually, this activity is supported by national and international laws and regulations, and is conducted according to the planning development and local needs: for instance if European and national policies have indicated as a priority the reduction of GHG emissions, probably the environmental criteria should result as more important than the economical ones, which evaluate the local convenience of the alternatives, e.g. the pay-back period of the investment needed for their implementation. Moreover, the criteria should be chosen in such a way that they are able to quantify the different impact of the options regarding a particular aspect: if different typologies of crop production are analyzed and the environmental pressures must take into account the associated GHG emissions, the amount of diesel fuel used during field operation, the fertilisers requirement and the quantity of the pesticides used may constitute accurate indications. On the other hand, these criteria may also supply additional information about other environmental aspects: higher amounts of fertilisers imply higher risks in terms of nutrient leaching and eutrophication, while the reduced use of pesticides limits the biodiversity losses.

Besides, some relative weights can also be established within a set of criteria in order to indicate which indicator is considered the most significant to evaluate a specific aspect of the examined options (see Fig. 2.4).

Fig. 2.4 Description of different typologies of weighting of the proposed criteria



Particularly, an MCA and the weighting phase may be developed by adopting a ranking or a rating methodology. The ranking methodology associates with each decision element a corresponding degree of importance, for example adopting specific questionnaires to be directly filled in by the decision makers. On the other hand the rating methodology provides to assign to each decision element a corresponding score (e.g. from 0 to 1 or from A to H) obtained evaluating all the identified criteria and summarising them in a global and unique score.

Moreover, it is important to highlight that each criteria can be applied using quantitative or qualitative indicators; an MCA can include both these typologies of indicators at the same time. This characteristic is very useful in a previous stage of the study when data of different levels of accuracy can be available to describe different aspects of the alternatives proposed.

Considering that each application of a specific indicator on the hypothesised alternatives implies the assignment of a relative score, alphabetical or numerical, it is important to know the range of variation of each indicator. Particularly, this knowledge allows to classify the obtained score with the aim to identify easily the suitability level of the examined option. The classes may be characterised by values of different nature: also in this case the values may be quantitative or qualitative, alphabetical or numerical. Usually, with the aim to promote an easy and immediate comprehension of the results, the numbers of classes are limited: for instance, if three classes are fixed it is possible to use high-medium-low or A-B-C or 1-2-3. Fig. 2.5 shows that from each typology of criteria the useful indicators have been identified in order to relieve the options characteristics; once the scoring of the indicator has been done, the associated value permits the identification of the relative class.

Therefore, the range where these indicators may vary must be previously known in order to define correctly the sustainability classes: in other words, this phase hypothesises a good knowledge of the sector where the alternatives are defined.

In any case the possibility to adopt a classification method for the obtained indicators allows to compare several typologies: once specific intervals of variation for each indicator have been established to reach the proposed objectives, the same sustainability class may be attributed to qualitative or quantitative indicators affecting different aspects (i.e. environment, economics, etc.).

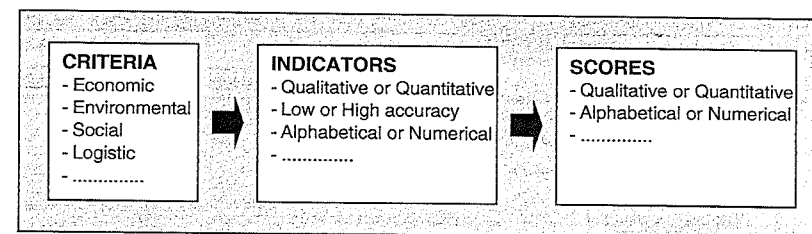


Fig. 2.5 Definition of criteria, indicators and scores evaluating the sustainability

Considering all the previous assumptions, the iterative nature of the MCA is quite evident in order to guarantee the mentioned properties of the used criteria and to improve the quality level of the study: for instance, with the aim to assure the completeness of the study, the introduction of a new criterion may be needed, otherwise to avoid the redundancy the merging of criteria able to describe similar effects may occur. Moreover, if the application of the MCA starts at the planning stage it must be considered that solutions identified as the most suitable at the beginning have to be monitored for several subsequent years in order to evaluate the effects produced: in this case the data of the MCA are integrated during the years, while the objectives fixed at the planning stage are verified in the successive steps (e.g. feasibility study) and eventually modified considering all the new inputs available.

Finally, time could be an important aspect in order to define the criteria of the MCA: for instance, some indicators could be described through a temporal function and assume different values or scores at the time passing. Particularly, some alternatives may obtain good scores at different time than others and, for example, may be profitable in the brief, medium or long period. Therefore, if the indicators require a specific time interval where they have to be observed, the time horizon used for the application of the MCA must be set in order to decide a priori, the most suitable period for comparing all the different options. In fact, it is important to assess both temporal and permanent effects associated with the alternatives, taking into account that different criteria may have different time horizons: economical criteria usually have a brief-medium horizon (e.g. the evaluation through the pay-back period in a maximum time of 5 years), whilst environmental ones may require a long term horizon (e.g. the carbon stock variations require a period of 20 years).

The next phase is about preference modelling: the decision makers provide to apply the criteria to the proposed alternatives and to calculate the relative indicators. This process may induce several problems because during its development it is possible to highlight some critical aspects of the previous stages: for example, the decision makers may indicate additional solutions or criteria, which may allow a better development of the MCA in order to reach the proposed objectives. All the assumptions originated during this phase may be integrated in the MCA according

**Table 2.1** Identification of the actors involved in the different phases of the MCA

Phase	Activity	Actors		
		Experts	Stakeholders	Decision makers
1	Problem identification		X	
	Objectives definition	X	X	
2	Alternatives identification	X		X
	Criteria definition	X	X	X
3	Scoring			X
	Weighting			X
4	Result aggregation			X
	Result analysis	X	X	
5	Discussion and Negotiation		X	X

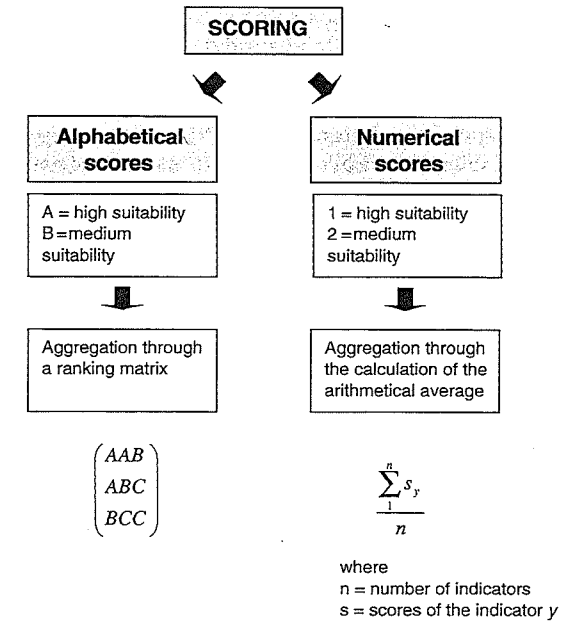
to its iterative nature, if considered necessary both by the experts and the stakeholders.

With the aim to avoid any misunderstanding it is necessary to highlight that the decision makers are the persons, who have the actual responsibility of the final decision and must indicate the most suitable solutions for the considered problem. They are required to take into account the opinions of both experts and stakeholders, but they cannot be catalogued as experts or stakeholders. On the other hand, the experts may be identified as technicians or academics working in the specific expertise sector of the problem under investigation, whilst the stakeholders are any single individual or group of people, who have an interest (e.g. a social or economical interest) in the examined problem. Table 2.1 identifies the actors involved in the different phases of the MCA.

It is important that, before the voting takes place, each decision maker has the possibility to expose to the others his opinion about the criteria and the relative indicators: particularly, it may be useful to know the indicators that are considered the most significant ones and why it may be affirmed this basing on the different points of view of the decision makers. Once this discussion has been carried out, each member must individually associate the scores with the various solutions, without declaring their choices in order to avoid any influence between the members themselves. The pre-voting discussion is fundamental because it is able to guarantee the interdiscipline of the process, promoting at the same time

- Compromises to accommodate the different needs;
- Interest in knowing all the different points of view;
- Respect for the competence of the other team members;
- Agreement between members about the objectives of the work.

Moreover, in this phase it is possible to decide to use some weights for the different typologies of the adopted indicators: these weights may be assigned a priori by experts on the basis of the literature or policies indications, or alternatively they may be indicated by each decision maker during the judgements definitions. In fact, weights may constitute a subjective approach to the problem

**Fig. 2.6** Different approach for scoring phase

and may be very different from one decision maker to another according to their background (e.g. technicians vs. politicians). For this reason, in some cases, the weights are previously decided as a compromise between all the different points of view, taking into account the relative importance of the indicators on the basis of the quality of the available data or of the importance of the associated criterion in respect to the other ones.

Once the judgements have been defined for each analyzed aspect of the proposed solutions, the aggregation of all the indicators scores must be done, taking into account also the associated weight. For each alternative the combination of all the assigned scores may be carried out following specific rules, that may differ very much because of the nature of the scores: particularly, if the alphabetical scores have been applied, the use a specific ranking matrix is needed, whilst, if numerical scores have been fixed, the associated arithmetic average can be calculated (see Fig. 2.6). Particularly, if the MCA is carried out using a numerical approach to identify the most suitable alternatives proposed to solve the problem, at the first stage scores are associated with each solution (scoring), whilst at the second stage some weights are also applied (weighting).

It must be highlighted that the application of specific weights is possible only if the independence between used criteria is assured. However, in this case, the MCA is a compensatory technique, because high values obtained on one criterion are compensated by low values on another.

When the most suitable solutions have been identified, stakeholders must analyze the obtained results and decide if there are some mistakes or unexpected outputs and if the solutions may be considered as satisfying. Obviously, if some problems or ambiguities are relieved, it is possible and necessary to reconsider all the steps of the decision process trying to identify some possible misunderstandings in the defined hypothesis or in the structure of the analysis.

Finally, the results must be discussed and it might be necessary to propose a negotiation between the stakeholders in order to reach a common interpretation of the results with the aim that all the stakeholders agree about the most suitable solutions identified by the MCA.

## 2.3 Generals About the LCA

The development of the LCA methodology began in the 1960s, with the aim to evaluate the problems related to raw materials and energy supplies in the industrial sector. One of the first studies developed following the LCA methodology was carried out for the Coca-Cola Company to compare the environmental benefits and drawbacks associated with the use of plastic or glass bottles [4]. This study quantified the raw materials and fuels needed and the environmental pressures due to the manufacturing processes for each beverage container. Afterwards other companies in both the United States and Europe performed similar comparative life cycle inventory analysis.

The process of quantifying the resource use and environmental releases of products had started to be known in the United States as a 'resource and environmental profile analysis' (REPA) while in Europe it was called an 'ecobalance'.

Currently, the LCA interests a large number of companies and industrial sectors, that use this approach to choose between alternative solutions during the design phase and/or the production phase. Also some governments and institutions have started to adopt the LCA as a valid instrument to associate with each product or service the environmental impacts caused during its production: the recent RED indicates the LCA to evaluate the benefits obtained through the use of biofuels instead of traditional fossil sources; the Ecolabel certifications are based on this approach; the Carbon Footprint methodology is directly linked and derived by the LCA, etc. In fact, during the previous decades customers and consequently the market has started to require additional information about the sustainability of the production processes, even if various researches demonstrate that all these data supplied by the industries do not significantly influence the trade and the relative profits. Moreover, because of the inappropriate use of the LCA by manufacturing industries, that begin to associate marketing claims with their products highlighting partial environmental benefits (the so-called "greenwashing" phenomenon), a standardisation process of the methodology was started. During the SETAC congress in 1993, the LCA name and acronym was fixed according to the first definition of the methodology: life cycle analysis is an objective instrument able to evaluate

the energetic and environmental loads for a process or activity, carried out through the definition of materials, energy and wastes flows. In addition, it is obvious that the assessment includes the whole life cycle of the process or activity, starting from the extraction and treatment of the raw materials, up to the manufacturing, transport, distribution, use and reuse, recycle and the final disposal. Finally, the procedures of the LCA were standardised in 1997 by the International Standard Organisation (ISO) through the ISO 14040 series updated in 2006.

The LCA is one of the tools of environmental systems analysis and it "provides a systematic framework, that helps to identify, quantify, interpret and evaluate the environmental impacts of a product, function or service in an orderly way" [11]. This technique allows to quantify the total environmental impacts of the provision of a product or service from original resources to final disposal, or so-called "cradle-to-grave". LCA is mainly a tool used for describing environmental impacts. Examples of other environmental systems analysis tools include risk assessment, environmental impact assessment (EIA), material flow analysis, environmental auditing, etc., but the LCA results as unique for its "cradle-to-grave" approach combined with its focus on products, or rather the functions that products provide.

All inputs from and outputs to the natural system, such as resource extraction and emissions, must be taken into account.

It is important to highlight some fundamentals of the LCA:

- This methodology is not able to analyze all the environmental pressures that a system can origin (e.g. landscape modifications, etc.), therefore usually the LCA results are integrated with evaluations obtained through the application of other methodologies (i.e. Environmental Impact Assessment);
- The LCA is a quantitative methodology, i.e. the impacts estimation is structured adopting specific indicators able to quantify the associated environmental impacts through numeric values;
- The LCA is used to evaluate the environmental impacts from a global point of view. In fact, this methodology considers all the processes that have permitted to obtain a specific product, and also all the processes concerning the extraction, treatment and by-products disposal of the raw materials needed. Therefore, no limits from a geographical or time point of view are previously fixed: for instance, the impacts due to the extraction process of a metal in Africa or South America are computed in the total impacts associated with a specific product which is produced in Europe during the final steps of the industrial chain;
- The LCA is a relative tool intended for comparison and not absolute evaluation, thereby helping decision makers compare all major environmental impacts when choosing between several alternatives.

For all these reasons the LCA is used to compare improvement options, to design a new product or to choose between comparable products. In fact one of the advantages of LCA is that it avoids "problem shifting" from one stage in the life cycle to another, from one environmental issue to another and from one location to another [12], because it takes the entire life cycle of the product and all



extractions from and emissions to the environment during that life cycle into account. According to these assumptions the LCA often shows unexpected and nonintuitive results: for instance, roses cultivated in Kenya and delivered to London by airplane transport may present lower GHG emissions than others cultivated in greenhouses in Netherlands (see the carbon footprint calculated at the Cranfield University, UK, as reported in the Economist the 17 of January 2008). Therefore, it is obvious that it is not correct to consider only one impact to determine, which alternative is the most profitable: for the roses case, for example also water management, land use modification and biodiversity losses should be considered and results obtained for these additional indicators could completely modify the final choice.

With the aim to identify some pros and cons of the LCA, it is important to know that the methodology is structured in four main steps (see Fig. 2.7):

1. Goal and scope definition. During this phase the objectives of the study, the functional unit, the system boundaries, the data needed, the assumptions and the limits must be defined. Particularly, the functional unit is the reference unit used to normalise all the inputs and outputs in order to compare them with each other;
2. Inventory data. This step concerns the analysis of the material and energy flows and the study of the system working. On the other hand the data collection for the entire life cycle implies the modelization of the analysed system. Moreover, one of the most critical aspects of this phase is the quality of the inputs, which must be verified and validated in order to guarantee the data reliability and correct use;
3. Impact assessment, evaluating the potential environmental impacts associated with identified inputs and releases through specific indicators usually fixed at the international level;
4. Impacts assessment and interpretation. In this phase the analyst aims to analyse the results and discuss them, helping decision makers to take a more informed decision. In addition, this step may highlight some problems in the LCA development which needs a more detailed approach: for instance, it can be decided to improve the quality level of some data collected from the literature because they describe a process which significantly influences an environmental pressure and therefore a more elevated accuracy of them may guarantee less variability in the results. This mechanism of the LCA assures the improvement of the results in an iterative way.

Concerning the inventory data it must be highlighted that the level of detail of the data collected determines the accuracy of the LCA results. However, the level of detail required to create the inventory depends on the size of the system and the purpose of the study: in a large system involving several industries with different production processes, certain details may not be significant contributors and may be omitted without affecting the accuracy or reliability of the results. These evaluations must be done during the goal and scope definition phase, taking into account the purpose of the work, the expected availability of the data, the financial

resources and also the time needed to develop the study. In addition, the quality level of the inputs may significantly vary according to the specific objective of the LCA: if the LCA is developed at a feasibility level in order to compare different alternative scenarios, the data would be simply estimated or obtained from the literature; whilst if the LCA is applied to an industrial process well known and defined, the data could be directly measured or collected through questionnaires.

In any case, even if the uncertainty in the final results do not allow to establish if one proposed solution is better than another, it must be assumed that the most important scope of the LCA is providing the decision makers (e.g. government officials, multinational corporations, nongovernmental entities (NGOs), or, ideally, multi-stakeholder panels) with a better understanding of the environmental and health impacts associated with each alternative. However, these indications about the environmental impacts should constitute only one component in the decision process because the evaluation done by the LCA is partial and is not able to describe all the environmental aspects associated with a specific process nor furthermore to assess its economical and social implications.

Therefore, the LCA presents some limitations which must be considered in order to correctly evaluate the role of this methodology as a decision support tool.

Data uncertainty and use of database are not completely transparent. In fact in order to develop an LCA it is important to collect and choose all the data inputs available for the process to be modelled, but all the data associated with the subprocesses are usually assumed by existent databases. These databases may be associated with a specific LCA software or also available free [8] as open-source but, in any case, it is impossible for a user to verify all the sources and all the data needed: actually, it is obvious that a lot of data inserted in the LCA are out of the control of the analysts and for this reason it is always important to indicate the software and references used in the LCA.

The LCA is not uniquely defined from the methodological point of view and different options are available according to the ISO standard. In fact different possibilities exist to deal with the co-products and/or by-products that are produced along the life cycle of a product: the allocation and the credit method.

The allocation is based on the concept that environmental impacts caused by a process are caused by the co-products and the main product. Therefore, the impacts (e.g. emissions) are allocated proportionately between the co-products and the main product. The allocation can be based on various criteria such as mass, energy content (e.g. lower heating value) or market prices.

However, the ISO standards recommend to avoid allocation wherever possible by expanding the product system, i.e. to use the so-called substitution method. It takes into account the further utilisation of co-products which usually substitute conventionally produced goods of the same use. For instance, olive tree pruning adequately treated may replace the methane to produce thermal energy in a medium-sized boiler or may be landfilled allowing some savings in chemical fertilisers. In any case, since the conventional product does not need to be produced for these expected uses, the avoided environmental impacts associated with their production are credited to the main product.

Both approaches are characterised by pros and cons and can lead to considerably different results. The substitution methodology delivers a more exact and close-to-reality picture. However, calculation is relatively complex and may result in a great bandwidth of results depending on the system boundaries chosen. Moreover, the subtraction of the credits that are given in the substitution method, under certain circumstances can compensate all expenditures. The reason is that many different use (and thus substitution) options are possible for the co-products. On the other hand, allocation constrains this variability at least to a certain extent as the further use of the co-products is not taken into account. It thus typically delivers more transparent and unambiguous results. The fact that both methods may deliver significantly different results is due to the mathematical way of obtaining the results.

In addition, it must be considered that the substitution method is also called the expansion system method, because actually the system boundaries are enlarged to include also processes that describe the treatment and reuse of the co-products. Obviously the definition of these processes often is only hypothesised without any assurance regarding their effective working, therefore the relative data are, usually, simply estimated or collected from the literature.

As highlighted in [10] the identification of the system boundaries have to be made carefully also regarding energy and materials embodied in infrastructures and equipments used during the entire life cycle. The cut-off of the system modelization must be done using the literature data and also applying the LCA in an iterative way: particularly information collected about similar studies and a preliminary development of the LCA where values are used from an existing database without inserting more detailed data, can highlight that some inputs are not significant in the calculation of certain impacts. This is the case of the construction materials of an airplane when the scope of the study is to evaluate the CO<sub>2</sub> equivalent emissions: the emissions related to the flights will be as high so that all the emissions due to the production phase of the airplane could be correctly considered negligible.

Finally, the application of the LCA to the agro-forestry sector presents several criticisms.

Usually, field operations may be responsible for the major part of the environmental pressures if compared with transport phase or subsequent treatments of the agricultural products. This is the case of the SRF producing the wood chips (see Chap. 4) or of the olive oil milling (see Chap. 5), where the tillage operations cause more than 45% of the total amount of CO<sub>2</sub> equivalent emissions. Obviously it depends on the impacts that are taken into account, but generally the GHG confirms this trend together with other possible indicators as the primary energy requirements; in contrast other indicators (i.e. wastes production) may imply different results. In any case, considering these assumptions, all the inputs associated with the field phase highly influence the results, therefore high accuracy in collecting these data is required, even if it is not so easy because usually they present a large variability [1]: for instance the amount of fertilisers applied depends on soil fertility and typology, whilst the diesel fuel consumption is

determined by the level of mechanisation, the power of the machines used, the morphological characteristics of the site, etc. In addition, although a lot of these data could be collected from the literature, it must be considered that all the references illustrate experimental data strictly referring to particular site conditions, which could be very different from those hypothesised for the LCA scenarios.

Additional criticisms may be introduced if some land use change must be detected. The LCA begins to include this analysis in its methodology when the production of bioenergy crops start to be studied in order to evaluate their sustainability. Particularly, determining the reference and the alternative land uses is fundamental in order to estimate some induced pressures on the environment, as carbon stock variations in soil and or vegetation. Moreover, since agricultural land is becoming increasingly scarce, more and more forest land or grassland is transformed into arable land. Such land use and land cover changes influence the area's carbon stock, i.e. the carbon content of both soil and vegetation. Any difference in carbon stock before and after cultivation has to be reflected in the greenhouse gas balances. Land use changes not only influence the climate but also factors such as biodiversity and habitat quality, soil functions and the water balance of a region. However, these impacts were not reflected by LCA up to now due to the lack of methodologies.

## 2.4 Generals About the Proposed Methodology

Considering all the MCA and LCA fundamentals, an approach able to integrate these two different methodologies has been developed. Particularly, at first the MCA has been applied in order to identify the more suitable solutions which in a second phase have been analyzed through the LCA in order to evaluate the environmental pressures more deeply.

In fact, for the environmental evaluation, it is needed to distinguish between local and global pressures that the agro-energetic chains may originate: for the first ones it is necessary to take into account the principles on which the EIA is typically based and which are included in the MCA; for the second ones the LCA methodology is needed.

In this way the effort and time needed for the LCA implementation have been significantly reduced because the methodology can be applied to a reduced number of scenarios once a large part of them has been classified as less profitable by the MCA.

The proposed applications illustrated in the following chapters regard very different chains of the agro-forestry sector. However, for all of them it has been hypothesised that they have been developed at the beginning of the planning stage or during the first step of the feasibility study. In this way the MCA and the successive LCA implementations have been used as a decision supporting tool in order to identify the most suitable design solutions.

Particularly, the MCA has been implemented considering the following steps:

- Goals definitions and decision makers typology;
- Scenarios definitions;
- Decision criteria identification;
- Criteria weights definition;
- Preference modelling obtaining the MCA results;
- MCA results interpretation.

During the goal definitions the operative scenarios have been defined considering the state of the art of the production or agro-energetic chains: in this phase, in order to evaluate all the different options and their different implications in terms of technical feasibility, cost/effectiveness analysis and environmental pressures, some literature review and experimental data collection have been carried out. In some cases the operative scenarios have been chosen hypothesising a specific geographical area, whilst in other cases the entire study has been based on generic data without considering the peculiarities due to the site specific characteristics. For instance, the yard scenarios in Chap. 3 have been based on the data of field operations and pruning management mainly referred to the Central Italy, whilst the Chap. 6 evaluates the convenience of establishing an oil palm plantation in an area where site conditions are not ideal without referring to a specific area around the world.

Taking into account that for each case study it has been hypothesised an application of the proposed methodology at the beginning of the design phase, the decision makers might be politicians, technicians and/or farmers.

All the applications have been structured first by identifying the main operative phases of each production or agro-energetic chain, secondly by defining for each phase all the possible scenarios and thirdly by combining together all the possible scenarios in order to define the whole production or agro-energetic chain, considering that each single choice in a specific phase may affect all the next ones. For each case study three categories of scenarios have been identified: one describing the field operations with particular attention to mechanisation, diesel fuel consumption and eventual use of nutrients and chemical compounds; one illustrating logistics and focusing on different means of transports, distances needed and storages organisation; one defining the plant of energy conversion or production.

It must be highlighted that in Chap. 6 the author has decided to introduce specific scenarios about the irrigation of oil palm cultivation in addition to them regarding the other field operations: this decision has been supported by the literature which highlights how often the oil palm is cultivated in areas characterised by low precipitation levels where irrigation is needed to reach the expected yields of fruits despite the high economical and environmental costs. Therefore, the MCA has to focus on this phenomenon in a separate way during the planning phase when the most suitable areas must be chosen in order to optimise the sustainability of the palm oil production.

Moreover, the logistics has been hypothesised in all the applications developed in a simplified way: in two applications (see Chaps. 5, 6) only the transport distances are considered whilst the vehicles typology is taken into account for the woody biomass production (see Chap. 4) and the storages organisation is analysed for the energetic use of agricultural residuals. These different approaches are due to the specific peculiarities and critical aspects of each case study: particularly, it is necessary to highlight that the logistics is often identified as the most problematic phase of the agro-energetic chains mainly from the economical point of view because of the low territorial density of the biomass and the seasonal nature of its supply which creates the need for a temporarily stockpiling before and after the delivery to the power, heat or processing plant.

During the decision criteria identification phase, for each case study a limited number of criteria have been fixed considering only two sustainability categories: environmental and economical. In fact, the MCA may be carried out considering a large number of additional possible principles considering different aspects, e.g. social, logistic, healthy, etc. aspects, and usually the choice of the principles taken into account must be supported by the necessity to reach objectives at a local, regional or global scale. As previously highlighted these objectives may be promoted by specific groups of stakeholders, i.e. politicians, technicians, customers, farmers, manufacturers, etc. Therefore, for the proposed applications only the economical and environmental criteria have been considered because these two typologies of criteria may be considered the most important ones for a large number of stakeholders: for instance, the economical criteria are certainly important for both producers/farmers and customers because the right solution can allow to minimise the market costs assuring a good level of competitiveness for the first ones and a profitable opportunity for the second ones; similarly, the environmental criteria may be considered fundamental for politicians, producers and customers in order to guarantee the environment preservation and a higher level of the life quality.

Moreover, for each criterion a measurable indicator has been identified and for each indicator three different levels of suitability have been defined. In this way, three values, alphabetical or numerical, may be assigned to each indicator: particularly, in all the proposed applications at the first stage of the methodology implementation the high level, i.e. the most profitable, has been identified by the letter "A", the medium level by the letter "B" and the low level by the letter "C", whilst in a second phase these alphabetical values have been converted into numerical.

Only for two cases analyzed in this work in Chaps. 3 and 6, criteria weights have been implemented adopting the "intra criteria" method described in Sect. 2.2. Assuming that the environmental and the economical criteria are characterised by the same level of importance, different weights have been associated to each indicator comparing it with the others of the same set of criteria. Moreover, the weights are numerical and allow to calculate for each scenario the environmental and the economical sustainability separately as weighted means associating with each criterion the corresponding indicator value multiplied for its weight.

Fig. 2.7 Components of a product life cycle assessment according to ISO 14040

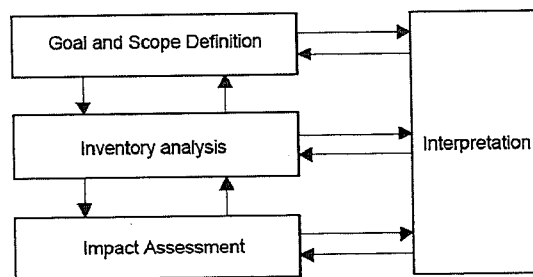


Fig. 2.8 Decision ranking matrix adopted for criteria scores combination

	A	B	C
A	A	A	B
B	A	B	C
C	B	C	C

The preference modelling has been carried out in two different ways: adopting alphabetical and/or numerical values during the scoring phase. As shown in Fig. 2.6 this phase has been first implemented in the proposed applications using the alphabetical scores and combining them through the decision ranking matrix illustrated in Fig. 2.8. Then the analysis of the obtained outputs has highlighted some criticism due to the large number of assumed criteria and reduced suitability level fixed for each criterion. Actually, the difference between the results of the scenarios, and mainly of the whole chains, has seemed insufficient determining a very limited number of chains at the "A" level despite a very large number of chains at the "B" level. For this reason the numerical scoring has also been applied by averaging the scores associated with each criterion on the number of environmental and economic criteria separately, and then making a final average between the two. The pros and cons due to the qualitative and quantitative approaches of the scoring phase have been compared more deeply in Chap. 5.

Once the MCA has selected the most suitable chains, the LCA has been applied to these alternatives in order to assess their environmental sustainability for a different point of view. As illustrated also in Chap. 3, for environmental evaluation, it is needed to distinguish between local and global pressures so that the agro-energetic or production chains may originate. For the first, it is necessary to take into account the principles on which the EIA is based; for the second, the LCA methodology is needed. Actually, during the last decades the relevance of the LCA in the food and agro-energetic sectors has been, respectively confirmed by the diffusion of different typologies of product certifications and by the recent indications of the EC (RED; [6]).

For each case study all the four phases of the LCA have been carried out according to the ISO standard and implemented all the inventory data in the software GEMIS 4.5 [7].

Particularly, the evaluation of the chains has been carried out comparing only two impacts calculated by the LCA: the GHG emissions through the CO<sub>2</sub>eq and the primary energy consumption through the cumulative energy requirement (CER). The choice of these two indicators allows to evaluate the relevant impacts for all the proposed applications, even if they supply partial information about the environmental sustainability excluding other emissions on soil, water and air. Moreover, the CO<sub>2</sub>eq emissions may be the first step for the environmental certification of the food products through the application of the Carbon footprint methodology, while they constitute the basis of the sustainability criteria proposed by the European Commission for solid and liquid biofuels (RED; [6]).

In this book, CO<sub>2</sub>eq emissions have been calculated through the following formula using the GWP indices for only three chemical compounds, i.e. CO<sub>2</sub> with GWP = 1, CH<sub>4</sub> with GWP = 296, N<sub>2</sub>O = 23, as proposed by the RED: Total Global Warming Potential [kg CO<sub>2</sub>equivalent] =  $\sum_i \text{GWP}_i \cdot m_i$

The CER indicator is used to evaluate the overall energy consumption of fossil fuels during the production of a particular product. During the eighties this indicator has been used in the agro-industrial sector as a result of the energetic analysis [9], in order to measure the embodied energy in goods and services. In addition, this indicator is a quantitative indicator and allows to estimate not only the energy used directly in manufacturing or in supplying goods and services (direct consumption), but also the energy required to make available raw materials and equipment required for the production process.

The LCA methodology has been applied to each case study using the substitution method through the boundaries extension approach, in order to evaluate the role of the by-products: for this reason the LCA results shown in Chaps. 5 and 6 include some credits for the alternatives which suggest the reuse of the residues produced along the chain. No allocation has been done even if the proposed chain has concerned only the by-products reuse: this is the case of the agro-energetic chain illustrated in Chap. 3, where no impacts due to the olive-grove management for the olives production have been associated with the olive trees pruning, but only the emissions caused by harvesting, treatment, transport and energy utilisation.

Concerning the field phase the use of agricultural machines has been considered in terms of both diesel fuel consumptions (indirect emissions) and the associated direct emissions during the operations. Particularly, for diesel fuel it has been hypothesised an LHV of 11.86 kWh/kg and a density of 0.8 kg/l, while the quantity of diesel fuel required during the field operations has been estimated considering an average utilisation of 60% of the nominal power of the machine and a specific fuel consumption of about 0.20–0.25 kg/kWh [3, 5].

Finally, the transports of the products have been modelled in the LCA taking into account that usually local transports within the farm are carried out with tractors equipped with rural trailers, whilst greater distances provide the use of trucks.

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## Chapter 3

# Energetic Use of Biomass and Biofuels

## 3.1 Introduction

Mediterranean countries produce 95% of the total world olive oil production estimated to be 2.4 million tonnes per year. Olive production is a significant land use in the southern Member States of the EU with important environmental, social and economical implications. The main areas of olive oil production are located in Spain (2.4 million ha), followed by Italy (1.4 million ha), Greece (1 million ha) and Portugal (0.5 million ha). France is a much smaller producer, with 40,000 ha.

In fact, data produced in 2000 by the EC's "Oliarea" survey [5] indicate a total olive area in Italy of 1.4 million ha, which represents a 400,000 ha increase compared with the area existing at the beginning of the 1990s and this is the tendency observed during the last decade. Moreover, based on data of the 5th Agricultural Census developed by ISTAT in 2000 and updated in 2005, the Tuscany region is characterised by a land use which promotes olive-groves occupying 18% of the total arable land.

However, in Italy there are several typologies of olive-groves because of different geographical area and site characteristics. Olive-groves may strongly differ by trees density which may vary from 50 to 400 plants/ha, from older plantations to the newer ones. Therefore, these different typologies of olive-groves require very different management practices: the lower tree density, the lower frequency of pruning operations of the trees crown.

The trees density also determines specific water requirements in order to assure elevated yields and to limit the competitions between the plants. For this reason the water availability is often considered as the most important limiting factor which, in fact, determines the olive-groves characteristics. Literature [5] declares that "under rain-fed cultivation, the lower the rainfall, the lower the tree density, by necessity". The water supply through an efficient irrigation system may assure sufficient yields even if the rainfalls are reduced, but the increases of the